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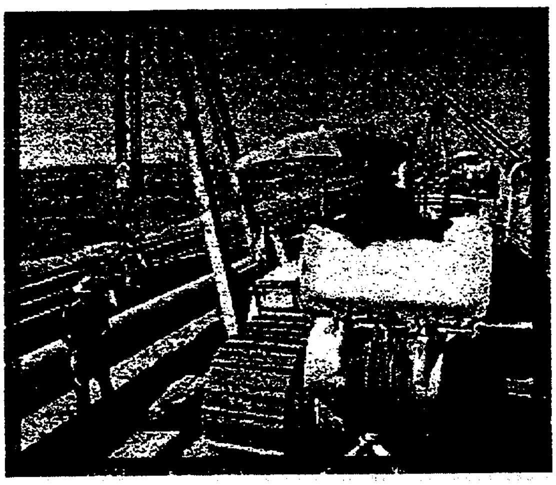

PIPELINE INSPECTION MAINTENANCE & PERFORMANCE INFORMATION SYSTEM

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EXECUTIVE SUMMARY

This report develops a practical methodology to calculate the probability of failure associated with corrosion flaws for a pipeline system. Two important concepts are utilized, one being the distribution of flaws in the pipeline, and the other being the rate of corrosion in the pipeline.

To estimate the distribution of flaws for the pipeline, the Weibull distribution is utilized, and it is demonstrated how such a distribution can be fitted to the data and then the relevant information extracted from the resulting distribution.

An example application is provided to demonstrate the calculation of probability of failure. To further illustrate the concept, Appendix B and Section 4 have been included. Appendix B demonstrates the calculation of the Weibull distribution parameters for various flaw sizes, and the results are analyzed in Section 4 of the report.

The impact due to failure is also analyzed, and a general empirical method is derived for obtaining the impact magnitude of the failure. Three categories are defined, high, medium and low impact, and guidelines are provided for determining which type should be expected upon failure. For a more in depth analysis, the impact assessment can be elaborated on as desired.

Finally it is recommended that the risk management process be implemented on a database, which can handle large amounts of information and can manage many various pipelines at the same time.

INTRODUCTION

Pipeline operating companies are looking to develop systems that will be able to perform the task of risk management. However, there are several obstacles that have to be overcome before such a risk management system can be effectively implemented. The major obstacle that has to be overcome is the lack of data available on pipelines.

For a risk management program, statistical variables have to be defined, values of which are usually provided for the reliability engineer in the form of data collected about the pipeline. In the case of pipelines however, there is very limited data available and therefore for the initial distribution of failure rates, only a sample from the whole population can be taken. There is hope however, because once the relevant variables are identified, data about these variables can be collected, and failure rate distributions can be fitted with increasing accuracy as more and more data is collected.

This report will focus on failure due to corrosion, managing the risk associated with corrosion, and the statistical analysis of corrosion related failures. Corrosion is only one failure mechanism associated with a pipeline however. The major failure modes are design related failures, third party damage failures, corrosion failures, and incorrect operation failures. These categories can then be subdivided further, depending upon the accuracy desired. If it is desired that these competing risks be included in the model, then certain statistical and probabilistic methods have to be employed which tend to get very convoluted. Modeling for competing risks will be left out of this report. Caution must be practiced however due to the fact that there will be less and less data available about more finely divided categories. It might not be practical to model some categories because the coefficient of variation would be very high.

Corrosion failures in pipelines are common, but usually are not catastrophic. As a pipeline ages, more and more corrosion associated flaws will develop on it's internal and external face, and each section of pipeline will have a distribution of flaws associated with it. If the distribution of flaws is known, along with operating conditions, the probability of failure can be calculated for one flaw and then a series system model can be utilized to find the probability of failure for the whole section.

Once the probability of failure for each section of pipeline has been calculated, the next step is to determine the impact of failure associated with the section. Larger flaws will influence failure in a more detrimental way than smaller flaws, so they have to be watched more closely. The model can be set up to find the probability of failure of the whole section, taking into account all the flaws at once, or flaw sizes can be divided into ranges and for each range a probability of failure can be calculated.

All failure probabilities, as calculated above, are done so for a given point in time, but it has to be kept in mind that with corrosion, flaw size distributions grow and will be time dependent. Therefore for every section of pipe, the flaw size distribution has to be determined relative to time. This in essence is a three dimensional distribution where one axis has the flaw sizes as a label, and the other axis would have time as an axis label. The third axis would be the probability of failure associated with each flaw size.

1.0 THEORY

There are many different methods available for modeling distributions. The exponential distribution is the simplest of distributions, but its applicability is limited. Unfortunately, the exponential distribution has a property called the memoryless property, meaning that the lifetime distribution of a new and used object modeled by the exponential distribution would be identical. In other words a used object would be as good as a new one. This of course is not the case for a pipeline.

Another distribution, the Weibull distribution, is a generalization of the exponential distribution that is appropriate for modeling lifetimes having constant, strictly increasing, and strictly decreasing hazard functions. Before going any further however, several definitions will be given about distributions to aid the reader.

1.1 Definitions

When discussing any type of distribution, there are five major functions that can be used to describe the distribution. The five functions define the distribution of a continuous, nonnegative random variable T, associated with a given system. There are also other methods to describe the distribution of T, but these other methods, like the moment generating function, the characteristic function, and the Mellin transform are not as popular and do not have intuitive appeal.

The five different functions that can be used to describe a distribution are the survivor function, the probability density function, the hazard function, the cumulative hazard function, and the residual life function. These five functions are briefly described next.

1.1.1 Survivor Function

The survivor function S(t), is a generalization of reliability. There are two interpretations of the survivor function; one: S(t) is the probability that an individual item is functioning at time t, and two: if there is a large population of items with identically distributed lifetimes, S(t) is the expected fraction of the population that is functioning at time t. The survivor function can also be described as the complement of the cumulative distribution function, F(t).

$$S(t) = P[T \geq t] \quad t \geq 0 \qquad \text{Eq.1}$$

$$F(t) = P[T \leq t] \qquad \text{Eq.2}$$

$$\therefore \mathrm{S}(\mathrm{t}) = 1 - F(t) \qquad \text{Eq.3}$$

1.1.2 Probability Density Function

The probability density function is defined by f(t) = -S'(t), where the derivative exists, and has the probabilistic interpretation

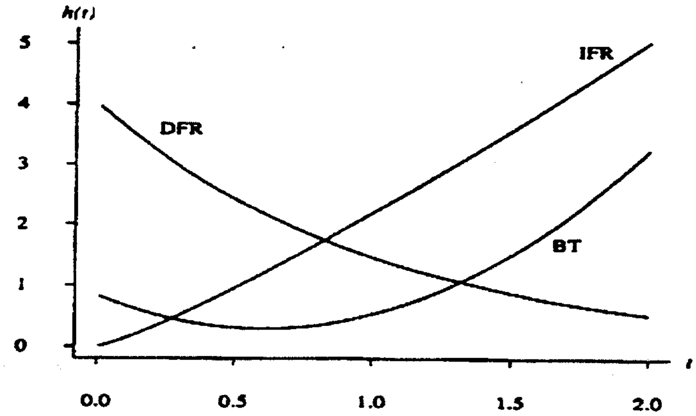

Figure 1.1: Illustration of various hazard functions.[2]

1.1.4 CUMULATIVE HAZARD FUNCTION

The cumulative hazard function, H(t), can be defined by

$$H(t) = \int_0^t h(\tau)d\tau \quad t \geq 0 \qquad \text{Eq. 8}$$

The cumulative hazard function is valuable for variate generation in Monte Carlo simulation, implementing certain procedures in statistical inference, and defining certain distribution classes.

1.1.5 MEAN RESIDUAL LIFE FUNCTION

The mean residual life function, L(t), is the expected remaining life, T-t, given that the item has survived to time t. The mean residual life function can be represented by

$$L(t) = E[T - t | T \geq t] = \frac{1}{S(t)} \int_t^\infty \tau f(\tau)d\tau - t \qquad \text{Eq.9}$$

The five distribution representations are equivalent in the sense that each completely specifies a lifetime distribution. Any one lifetime distribution representation implies the other four. Algebra and calculus can be used to find one lifetime distribution given that another is known. Table 1.1 illustrates the relationship between the various lifetime distributions.

calculate the probability of failure associated with each flaw range. Once the probability of failure due to a certain sized flaw is determined, the next step is to take into account the number of flaws there are of this certain size.

The best way to model the failure of a section of pipe, or in this case a pipeline system, is to set up a series system. In a series system if one flaw results in failure, then the whole system fails and the pipeline is taken out of operation. This can be represented in the following way

$$P_{fSystem} = 1 - \prod_{i=1}^{n}\left(1 - P_{f_i}\right) \qquad \text{Eq.14}$$

Where P_{fi} is the probability of failure associated with a certain sized flaw. In the case of equal probabilities of failure, as would be associated with a certain number of equivalent sized flaws the previous equation would reduce to

$$P_{fSystem} = 1 - \left(1 - P_{fIndividual}\right)^{n} \qquad \text{Eq.15}$$

where n is the number of flaws of a certain size that are present in the system.

Another important consideration is accounting for the periodic repair of the system. Usually, in the case of pipelines, the smaller sized flaws are disregarded because they are numerous and are difficult to fix individually unless the whole section of pipe is removed. Also in the case of a series system, components that have very low reliabilities should be removed, because they decrease the reliability of the whole system extensively. Therefore usually the larger flaws are fixed and therefore the reliability of the system greatly improves, given that there aren't a significant number of smaller flaws in the system. A plot of system reliability versus component reliability is shown in Figure 1.2. The most important concept that this graph shows is that a small increase in component reliability nets a substantial increase in system reliability for a system with a large number of components.[2]

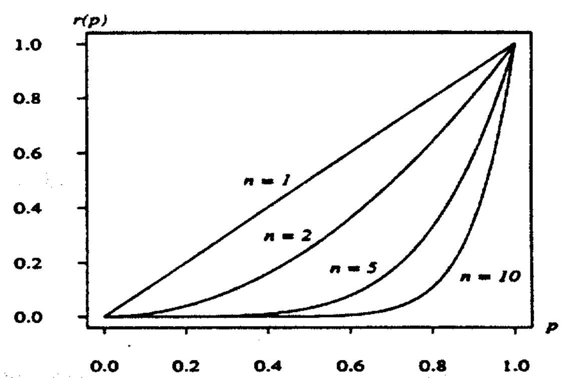

Figure 1.2: Component reliability versus system reliability for a series system.[2]

for n = 0, 1,...[2]

For NHPPs, the times between events are neither independent nor identically distributed. The time to the first event in an NHPP has the same distribution as the time to the first event of a single nonrepairable item with a hazard function $\lambda(t)$. The times between these subsequent events do not necessarily follow distributions like the Weibull distribution.

The next step in the risk management of pipelines is to obtain the parameters necessary to develop an appropriate distribution for various flaw sizes over a given time period.

1.4 Parametric Estimation for the Weibull Distribution

To estimate the scale and shape parameters of a Weibull distribution two different methods can be used. One method utilizes mathematical formulas and becomes very cumbersome when only limited calculation abilities are available. The reason for this is that the Weibull distribution does not have a closed form maximum likelihood estimator for its parameters. The mathematical method can be seen in Appendix A.

The second method of solving for the fitting parameters of the Weibull distribution is to use graphing techniques. Prior to the widespread use of computers for reliability analysis, "Weibull paper" was used to determine if the Weibull distribution was an appropriate model for a data set. To apply the Weibull distribution to estimate the number of flaws in a pipeline distributed according to time, data must be available, but usually in the beginning there is little if any data that can be fitted. Therefore, for the initial estimate some common sense and expert knowledge should be utilized. It should be noted however that the Weibull distribution was chosen because it is a relatively simple distribution to use for our purpose, but if in the future it is discovered that another distribution better answers our purpose then a switch can be made. For the time being however, we will work with the Weibull distribution.

Previously the survivor function was defined as

$$S(t) = e^{-(\lambda t)^{\kappa}} \qquad \text{Eq.18}$$

which can be transformed into the cumulative distribution function by subtracting the survivor function from 1

$$F(t) = 1 - e^{-(\lambda t)^{\kappa}} \qquad \text{Eq.19}$$

At this point the scale parameter, λ, is rewritten as $1/\sigma$, in order that the calculations are more easily performed. Now the equation for the cumulative distribution function can be rewritten in the form

$$\frac{1}{1 - F(t)} = e^{\left(\frac{t}{\sigma}\right)^{\kappa}} \qquad \text{Eq.20}$$

2.0 APPLICATION OF THE THEORY TO PIPELINES

Before any answers can be obtained using the above outlined theory, it is necessary to divide the problem into relevant parts. This is necessary due to the fact that this reduces the amount of computation needed, and makes the whole problem more manageable.

To make the problem easier to handle, the first step is to decide what ranges for flaw sizes should be used. Instead of obtaining distributions for an infinite number of flaw sizes, the effort will be concentrated on obtaining distributions for various categories of flaw sizes. The obtained distributions will then try to compensate for a certain range of flaw sizes below and above a certain value of the flaw size. For example if one distribution is obtained for ¼ inch flaws and another for 1 inch flaws, then the 1 inch distribution can be designed to compensate for flaws ranging from ¾ inches to 1 ¼ inches.

Depending on the accuracy desired, distributions can also be calculated for various sections of the pipeline. Of course this requires more work and depending on how accurately corrosion can be predicted in the pipeline, it might not even be worth the effort since the confidence level of the output would be very low. If the pipeline can be pigged however, this would be an ideal task to perform in order that a better understanding is achieved of the corrosion risk management of the pipeline.

For the purpose of this report only certain general categories of flaw sizes and corrosion magnitudes will be considered, in order that the procedure can be demonstrated. To apply the risk management technique to a specific pipeline, several characteristics of the pipeline would have to be considered, and the corrosion rate calculated using the many available corrosion loss formulas. Once the corrosion rate and loss is calculated for a pipeline, the distribution of flaws can be determined and the appropriate fitting distribution chosen.

2.1 Range of Flaw Sizes

As was mentioned earlier, this report will only address a certain range of flaw lengths. It should be noted first that the burst strength of a pipe is more strongly affected by circumferentially oriented flaws as opposed to longitudinal flaws. Therefore, a limit will be set on the maximum length of flaws for which the probability of failure will be calculated. This length is designated to be the nominal diameter of the pipe. Flaw lengths greater than the diameter of the pipe have a very low frequency of occurance, and it presumed that they require a long amount of time to develop. The pipe diameter that will be used throughout this report will be 8 inches. This value will represent the outside diameter of the pipeline. Once the diameter of the pipeline is known so is the size of the largest flaw.

Next, various ranges of flaw sizes will be chosen below 8 inches, for which distributions will be determined. The midpoint of these various ranges can be represented by 5 inches, 2 inches, 1 inch, and ¼ inches. It is important to note however that when that probability of failure is calculated the depth of each of these flaws also needs to be known. The above values only represent lengths for

	VERY CORROSIVE	MILDLY CORROSIVE	NOT CORROSIVE
Temperature Range	$>100^0$ F	100^0-70^0 F	$< 70^0$ F
Amount of Oxygen in System	> 100 ppb	20 to 100 ppb	< 20 ppb
Amount of Hydrogen Sulfide in System	> 1.5 psia	1.5 to 0.05 psia	< 0.05
Type of Flow in System	Pseudo Slug / Slug Flow	Plug Flow	Stratified Smooth Flow
Amount of Water Present in System	>15%	14 to 5%	<1%
Particles Present in System (Significant Concentrations)	D > 50 mils	10 < D < 50 mils	D < 10 mils
Coating Lifetime	1 to 5 years	6 to 14 years	>15 years
Coupon Rates	> 5 mpy	0.1 to 5 mpy	< 0.1 mpy

Table 2.1: Evaluation of environmental descriptor.

Next, an indexing technique is used to calculate a score for each type of pipeline that is being evaluated. For each category, very corrosive to not corrosive a range of index values must be assigned. In this case, the range chosen is from 1 to 3, where the lower scores indicate unfavorable conditions and the higher scores are reserved for pipelines that are in a relatively non-corrosive environment. So the value of 1 corresponds to very corrosive, 2 corresponds to mildly corrosive, and 3 corresponds to not corrosive. Once all the above parameters have been scored the total score must be tallied up. The total score is calculated by adding all the values obtained for the various parameters.

Once the total score is known, it is necessary to know what ranges correspond to a specific environment. The table below shows how the ranges can be evaluated.

	VERY CORROSIVE	MILDLY CORROSIVE	NOT CORROSIVE
Cumulative Score	8 to 13	14 to 21	22 to 24

Table 2.2: Evaluation of cumulative score for environmental descriptors.

2.2.1 COATING EFFECTIVENESS

At this point a short chapter is dedicated to coating effectiveness, due to the fact that many times it will be difficult to evaluate how effective a coating really is.

environment, can be found in Appendix B. It should also be remembered that the calculations are based on the premise that the pipeline is constructed of mild steel.

It was mentioned before that larger flaw sizes will be less frequent than smaller flaw sizes, therefore the distribution for 1 inch sized flaws should fall between the ¼ inch and the 2 inch flaw size distributions. Due to the fact that there is no real data available for the calculations, a limit will be set as to how many flaws can develop in an 8 inch diameter pipe over a certain period of time given that the environment is very corrosive. For this task an educated guess will be made, and it must be kept in mind that when the calculations are applied to an existing pipeline it might be possible to *estimate* the flaw size distribution for the pipeline from a small section of the pipeline. Also operators who have been working in the field for extend periods of time, will be able to make educated guesses about the flaw size distribution in a pipe even if there isn't much data available.

For this estimate calculation the following data, presented in Table 2.3 was collected about 1 inch flaw sizes in an 8 inch diameter mild steel pipe that was in service in a very corrosive environment:

OBSERVATION NUMBER	DURATION TO DEVELOP 2000 1 INCH FLAWS PER MILE (DAYS)
1	730
2	912
3	1000
4	1130
5	1250
6	1345

Table 2.3: Data used for sample calculations.

The next step is to see if the Weibull distribution is an appropriate distribution for the obtained values. In order to determine this, a plot of $\ln\ln(1/1\text{-}F(t))$ versus $\ln(t)$ has to be constructed. If the data follows the trend of a line, then the Weibull distribution is an appropriate distribution for the obtained numbers, and the shape and scale parameters can be determined from the plot. The plot of the values in Table 2.2 can be seen in Figure 2.1.

2.4 Calculating the Probability of Failure for a 1 inch Flaw Size

To calculate the probability of failure for a 1 inch flaw size the classic demand-resistance model will be used, where the demand will signify the operating pressure, and the resistance will be the burst pressure of the pipe, given that there is a 1 inch flaw present. It should be noted here that to make the calculations easier, corrosion for all flaw sizes can be taken as uniform, meaning that a flaw size that is 1 inch long and a flaw size that is 8 inches long will have the same amount of corrosion loss. Therefore after the corrosion loss in the pipeline for a particular year has been calculated, the value obtained can be applied to all flaw sizes.

To continue the example, it will be presumed that in this "very corrosive" environment, the corrosion rate is 50 mils per year, and we wish to calculate the probability of failure due to 1 inch flaws in the pipe after a time of 3 years. We will take the pipe wall thickness to be 0.30 inches. The operating pressure will be taken as 1500 psi.

Therefore after 3 years, the pipe wall thickness is expected to be 0.30 – 3(0.05) inches, which is equal to 0.15 inches. The next step is to calculate the burst strength of the pipe, which can be done using the following equation

$$P_{burst} = f_{wl} \frac{t^*}{R} \left[\frac{1}{2} + \frac{1}{\sqrt{3}} \right]^{n+1} \sigma_{uts} \qquad \text{Eq.24 [9]}$$

In the above equation f_{wl} accounts for the increase in strength provided that the wall loss only occurs in the 1 inch flaw. Variable n is the strain hardening index of the steel, usually on the order of 0.05 to 0.15, t^* is the corroded pipe wall thickness, R is the mean radius, and σ_{uts} is the ultimate tensile strength of the pipe. The value of f_{wl} is given by the following formula

$$f_{wl} = \left(\frac{2}{1+\phi} \right)^n \qquad \text{Eq.25 [9]}$$

where ϕ is the fraction of the pipe wall that has corroded, mainly the 1 inch flaw length. In this case ϕ is equal to $1/[(8-0.6)\pi]$ or 0.043 (4.3% circumferential wall loss; 8 - 0.6 equals the inner diameter of the pipe). If n has a value of 0.15 then f_{wl} equals 1.10. If the ultimate tensile strength of the pipe steel is 100,000 psi, then the burst pressure when a 1 inch flaw present is 2334 psi.

The probability of failure now can be calculated using the following equation

$$p_f = 1 - \Phi \left(\frac{\ln\left(P_{burst} / P_{operating} \right)}{\sqrt{\sigma_{\ln_b}^2 + \sigma_{\ln_o}^2}} \right) \qquad \text{Eq.26}$$

3.0 IMPACT ASSESSMENT

The ultimate goal of risk management is to reduce the risk associated with an operation. Usually an engineer will describe the risk in terms of dollar values, due to the fact that these type of units are more meaningful to management. Of course though, each dollar value is associated with an impact, which in turn is related to the type of failure that the pipe will experience. Failure of large flaws, even though less prevalent in the system will tend to have a greater impact than smaller flaws. The gravity of the impact is also directly related to what type of area the pipe is located in. For example, if failure of a pipeline occurs in an area where some sensitive animal species are present, or where people can get hurt, the impact in terms of dollars experienced by the owner of the pipeline will be considerably higher than if the failure occurred in a remote unpopulated area.

Therefore to be able to make the appropriate decision as to how to manage a pipeline it is crucial that the impact associated with a certain type of failure be known. The expected cost of the failure can then be calculated by multiplying the probability of failure by the cost of failure. Again it is crucial that the impact due to various failure types be distinguished. The type of mitigation chosen also has a cost associated with it, therefore this cost also has to be considered before an action is taken.

It is also important to take note of the type of detection and isolation systems that are present on the system because how early the leak is detected and isolated directly influences the magnitude of the impact due to the leak. In this section an indexing method is going to be developed for the impact assessment due to the failure of pipelines, where three major categories of impact will be distinguished. One category will be high impact, another moderate impact and a third, low impact. High impact for example will be associated with failure of pipelines that carry hazardous materials that are in close vicinity to populated areas, or whose failures can have a detrimental effect on the surrounding environment.

3.1 Impact Influencing Operational Characteristics

In this section several characteristics of the pipeline are going to be listed and ranked according to the impact that they are expected to have. This is going to be performed for a 1 inch flaw size which can later be adjusted to compensate for other flaw sizes. To accomplish this, several important questions need to be asked:

- Are there people in the area?
- Is the area rural or urban?
- What is the leak detection method and threshold?
- How do you stop the leak?
- What will the product do when it leaks?
- What are the properties of the product?
- How do you clean up the product?

determine when material is leaking, and finally the least efficient method of detection is visual detection or detectors with marginal coverage.

3.1.4 LEAK ISOLATION METHODS

Just like leak detection systems, leak isolations systems can also be grouped into three different categories. The most efficient isolation system is one where isolation or shutdown systems are activated without operator intervention, and there are detectors and instrumentation present. Next in efficiency are isolation or shutdown systems that are activated by operators from a control room and finally the worst case scenario is when isolation is dependent on manually operated valves.

3.1.5 PRODUCT CHARACTERISTICS UPON RELEASE

There are many different types of materials that can be transported by pipelines, and when failure occurs and the product is released, not all materials will behave equally. Therefore it is crucial to determine the effect that release will have upon the material. For example, certain liquids when released might turn into gas, or they may just form a liquid pool. Depending upon the characteristics upon release, the product may also be more likely to ignite and cause further damage. For gases ignition would mean an explosion would occur. In general, gas lines and highly flammable fuel lines are considered high impact, meanwhile oil and multiphase pipelines having a high liquid to gas ratio (> 2:1) are considered to be in the moderate impact category. The low impact rating is reserved for pipelines that carry water.

3.1.6 PRODUCT HAZARD RATING

If pipelines carry very hazardous materials like hydrogen sulfide gas, which is very toxic, consideration must be given to the impact of such a highly toxic gas. Oil on the other hand will not be as toxic to humans, but if it is in the ocean, a lot of wildlife may be affected in a negative manner. For the sake of simplicity most materials carried by pipelines, especially from offshore, will have a hazard rating that brings about a moderate to high impact upon release. For example gas pipelines are considered high impact on land and offshore, but oil pipelines can be classified as having a moderate to high impact depending on whether the shoreline is sensitive or not.

For example, failure of many offshore pipelines can seriously impact the shoreline and animals living in the water. On land however, the same failure will only have a moderate impact, depending on the viscosity of the fluid and the permeability of the soil.

3.1.7 PRODUCT CLEAN-UP

The cleanup of an oil spill can usually cause a lot of headache, due to the fact that special environmental considerations have to be followed. This of course is the by oil. Fog may severely restrict skimming operations and at times prevent overflights to locate oil concentrations and to direct the necessary equipment.

The cleanup might be complicated by oil lying submerged in the nearshore surf zones, adjacent to the areas most heavily affected. New impacts from the submerged oil might become a daily occurrence thus repeated beach cleanings are necessary.

To obtain a bound on the impact of the oil spill and the effort associated with the cleanup, the sensitivity indexes will be utilized. For example, a sensitivity index of 1 or 2 will be considered a low impact while, sensitivity indexes ranging from 6 to 10 are considered high impact. Moderate impact coincides with sensitivity indexes of 3, 4 or 5.

3.1.8 PRODUCT DISPERSION

The dispersion of the product upon release strongly affects the impact that the failure has upon the surrounding environment. Gases are usually dispersed into the air, and the greatest concern is whether the wind will carry it to a certain site where a lot of people might be affected, or will the gas just diffuse and have a very low impact.

Of course the impact of the gas release is strongly related to the amount of gas released, which is usually large when a rupture occurs, and there is a sudden release. High-pressure lines are prone to ruptures, and should be given extra special care. The type of material and the line pressure both are important factors relating to the dispersion of the material. Oil on the other hand will tend to pool or run off, depending on the terrain, and if it is in the ocean then it will tend to form a sheen on the surface of the water.

To categorize the impact due to dispersion, surface area amounts were chosen to represent low, moderate and high impacts. For a low impact rating an affected area of 5000 square feet or less was designated, and for a high impact rating an affected area of 1 square mile or greater was designated. The moderate impact value lies between the value of the low and high impact.

The dispersion of the material can be ascertained from the Bernoulli equation and through the application of fluid and gas dynamics. These methods will not be discussed here, but are only mentioned as a reference.

Table 3.2 has been developed to ease the decision-making procedure and summarizes all of the previously derived rating criteria.

Table 3.2: Impact scoring summary.

	LOW IMPACT SCORE: 1-10	MODERATE IMPACT SCORE: 11-20	HIGH IMPACT SCORE: 21-30
Number of people in area	1 or less	1 < # < 5	5 or more

decrease the probability of failure without decreasing the operating pressure. On the other hand future deterioration of the pipeline can be inhibited through the use of corrosion inhibitors and periodic cleaning of the pipe. Sections where larger flaws exist in the pipeline, specific repair options are usually available. The pipeline can be repaired at these locations by either replacing the old section or through hot tapping or patching the pipeline at the specific location of the flaw.

The key of course is to correctly assess the corrosion mechanism present in the system, and therefore have a reliable method of predicting failure probabilities for the pipeline. Only then can a decision be made with confidence.

4.0 EXAMPLE

In this section a set of distributions is going to be developed for a mildly corrosive environment, and the various lifetime distributions plotted for each. It is also going to be discussed how these distributions can be easily adjusted to fit very corrosive to non corrosive environments.

In Appendix B, several hypothetical distributions were calculated for flaw sizes ranging from ¼ inches to 8 inches. The ranges for which calculations were performed were for ¼ inch flaws, 1 inch flaws, 2 inch flaws, 5 inch flaws and 8 inch flaws. Table 4.1 shows the assumptions used to develop the distributions.

	¼ inch	1 inch	2 inch	5 inch	8 inch
Number of Flaws upon which Distribution is Based	300	150	75	25	5

Table 4.1: Number of flaws upon which distributions were based.

The number of flaws were chosen randomly for this example, but when this technique is being applied to an actual pipeline, it is best to examine samples of failed pipe sections, and try to derive a representative number of flaws for which the distribution can be calculated for. Of course a more exact answer can be obtained by continuously observing the growth of flaws and each time an inspection is done to record the number of flaws present in the pipe. If in depth measurements can not be made then an upper limit for the flaw sizes can be chosen and a distribution calculated for the chosen number of flaw sizes. It should also be kept in mind that the distribution will partially correct for the fact that only the upper limit of flaw sizes was chosen. This is true because the probability of finding 75, 2 inch flaws before 5 years will be smaller than finding 20, 2 inch flaw sizes before 5 years. Due to the increased number of flaws though, when calculations are being carried out for the series of 75 flaws a higher probability of failure is going to be obtained. Table 4.2 illustrates the example.

	Probability of Failure (series system)	Likelihood of x Number of Flaws
20, 2 inch flaws	Lower	Higher
75, 2 inch flaws	Higher	Lower

Table 4.2: Self correcting tendency of model.

Of course it should be noted that it does not mean that the two calculations for different flaw sizes will be the same, but the answer should not be vastly different.

The lifetime distributions for the flaw sizes and numbers can be seen in Figures 4.1 through 4.4.

4.0 EXAMPLE

When the hazard function is integrated the cumulative hazard function is obtained, which gives the information: how many flaws may be expect by a certain time t. For example, looking at Figure 4.4 for 8 inch flaw sizes, at time 8000 (~22 years) the cumulative hazard function is about 2, which means that at this time the hazard has doubled, and there might be 10 instead of 5, 8 inch flaws present in the system.

After the first 5, 8 inch flaws are found, the occurrence of the next 5 can be calculated from equation 17, given that the intensity function for the failures can be determined.

$$P[N(b)-N(a)=n]=\frac{\left[\int_a^b \lambda(t)dt\right] e^{-\int_a^b \lambda(t)dt}}{n!} \qquad \text{Eq.17}$$

The hazard function previously calculated can be substituted for the intensity function and the value of the above equation will give the probability of the next 5, 8 inch flaws (n =1). This value of course will be somewhat different from that obtained by using strictly the cumulative hazard function. The value that is obtained of course depends upon the time interval being analyzed. Before a decision is made, the depth of the corrosion must also be taken into account.

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9. F. J. Klever, G. Stewart. *New Developments in Burst Strength Predictions for Locally Corroded Pipes*. Shell International Research, March 1995

APPENDIX A [2]

If a set of data points is available then to solve for the parameters of the Weibull distribution, the following equation can be used to find the scale parameter.

$$\lambda = \left(\frac{r}{\sum_{i=1}^{n} x_i^{\kappa}} \right)^{1/\kappa} \qquad \text{Eq. A1}$$

where x is equal to the time to develop a certain number of flaws of a specific size, and r is the event that 200 flaws develop. To solve for κ however the numerical procedure becomes more cumbersome. The following equation must be solved to obtain a value for κ.

$$g(\kappa) = \frac{r}{\kappa} + \sum_{i \in U} \log x_i - \frac{r \sum_{i=1}^{n} x_i^{\kappa} \log x_i}{\sum_{i=1}^{n} x_i^{\kappa}} = 0 \qquad \text{Eq. A2}$$

The above equation must be solved iteratively. One technique that can be used here is the Newton-Rhapson procedure, which uses

$$\kappa_{i+1} = \kappa_i - \frac{g(\kappa_i)}{g'(\kappa_i)} \qquad \text{Eq. A3}$$

The derivative of g(κ) reduces to

$$g'(\kappa) = -\frac{r}{\kappa^2} - \frac{r}{\left(\sum_{i=1}^{n} x_i^{\kappa}\right)^2} \left[\left(\sum_{i=1}^{n} x_i^{\kappa}\right)\left(\sum_{i=1}^{n} (\log x_i)^2 x_i^{\kappa}\right) - \left(\sum_{i=1}^{n} x_i^{\kappa} \log x_i\right)^2 \right] \qquad \text{Eq. A4}$$

For the initial estimate of κ, the following equation has been developed by Menon (1963).

$$\kappa_o = \left\{ \frac{6}{(n-1)\pi^2} \left[\frac{\sum_{i=1}^{n} (\log x_i)^2 - \left(\sum_{i=1}^{n} \log x_i\right)^2}{n} \right] \right\}^{-1/2} \qquad \text{Eq. A5}$$

APPENDIX B

This section presents a hypothetical situation of a pipeline that has a mildly corrosive environment and a various number of flaws different sized flaws. Hypothetical data is provided and analyzed. For each flaw size the various lifetime distributions are plotted and can also be seen in section 4 of the report.

The four lifetime distributions that are plotted are the survivor functions, the probability density functions, the hazard functions, and the cumulative hazard functions. The methodology used to find the fitting parameters for the distributions is outlined in Section 2.

Table B1

Time to develop 300, 0.25 inch flaw sizes over a length of 1 mile.

Observation Number	Time (years)	Time (days)	ln(t)	lnln(1/1-F(t))
1	3	1095	6.999	-2.013
2	4.5	1642.5	7.404	-1.246
3	5.5	2007.5	7.605	-0.755
4	7.8	2847	7.954	-0.367
5	9	3285	8.097	-0.019
6	11	4015	8.298	0.327
7	12	4380	8.385	0.732
8	13.1	4781.5	8.473	

Slope	Intercept
1.8553	-14.986

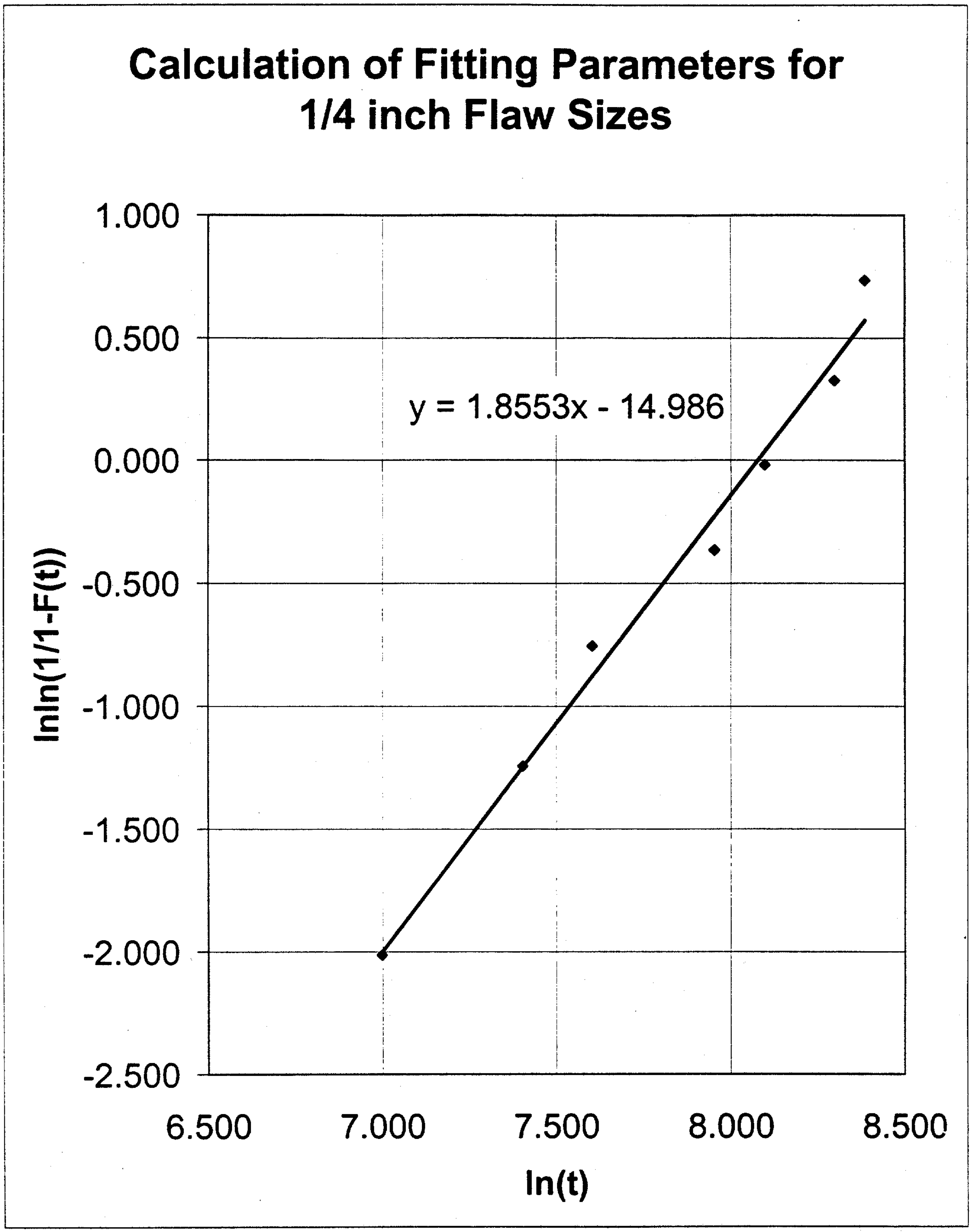
κ	λ
1.8553	0.00031

Fitting Parameters

Table B2

Various Lifetime Distributions for 1/4 inch Flaw Sizes

Time (Days)	S(t)	f(t)	h(t)	H(t)
500	0.969	1.134E-04	1.171E-04	0.032
1000	0.892	1.890E-04	2.118E-04	0.114
1500	0.785	2.352E-04	2.996E-04	0.242
2000	0.662	2.535E-04	3.832E-04	0.413
2500	0.535	2.483E-04	4.638E-04	0.625
3000	0.416	2.256E-04	5.421E-04	0.877
3500	0.311	1.926E-04	6.185E-04	1.167
4000	0.224	1.555E-04	6.933E-04	1.495
4500	0.156	1.194E-04	7.668E-04	1.860
5000	0.104	8.744E-05	8.391E-04	2.261
5500	0.067	6.126E-05	9.104E-04	2.699
6000	0.042	4.113E-05	9.807E-04	3.172
6500	0.025	2.651E-05	1.050E-03	3.679
7000	0.015	1.642E-05	1.119E-03	4.222
7500	0.008	9.787E-06	1.187E-03	4.798
8000	0.004	5.618E-06	1.254E-03	5.408
8500	0.002	3.108E-06	1.321E-03	6.052
9000	0.001	1.658E-06	1.387E-03	6.729
9500	0.001	8.538E-07	1.453E-03	7.439



Calculation of Fitting Parameters for 1/4 inch Flaw Sizes
y = 1.8553x - 14.986
1.000
0.500
0.000
-0.500
-1.000
-1.500
-2.000
-2.500
lnln(1/1-F(t))
6.500
7.000
7.500
8.000
8.500
ln(t)

Table B3

Time to develop 150, 1 inch flaw sizes over a length of 1 mile.

Observation Number	Time (years)	Time (days)	ln(t)	lnln(1/1-F(t))
1	4	1460	7.286	-2.013
2	5.2	1898	7.549	-1.246
3	6	2190	7.692	-0.755
4	7.5	2737.5	7.915	-0.367
5	9.4	3431	8.141	-0.019
6	10	3650	8.202	0.327
7	13	4745	8.465	0.732
8	16	5840	8.672	

Slope	Intercept
2.2817	-18.486

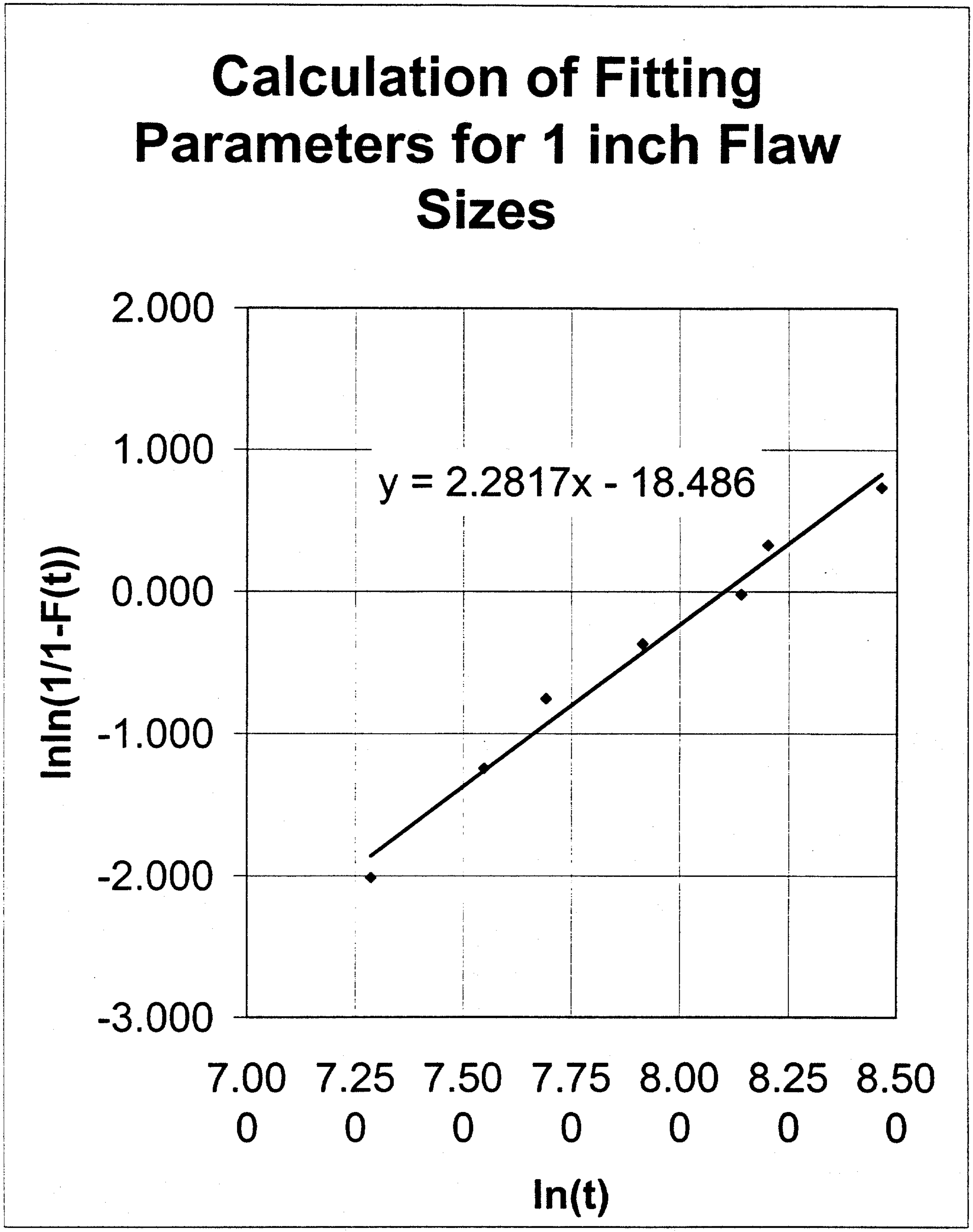
κ	λ
2.2817	0.000303

Fitting Parameters

Table B4

Various Lifetime Distributions for 1 inch Flaw Sizes

Time (Days)	S(t)	f(t)	h(t)	H(t)
500	0.987	6.072E-05	6.154E-05	0.013
1000	0.937	1.401E-04	1.496E-04	0.066
1500	0.848	2.132E-04	2.516E-04	0.165
2000	0.727	2.645E-04	3.638E-04	0.319
2500	0.588	2.849E-04	4.842E-04	0.531
3000	0.447	2.737E-04	6.117E-04	0.804
3500	0.319	2.376E-04	7.453E-04	1.143
4000	0.212	1.876E-04	8.844E-04	1.550
4500	0.132	1.353E-04	1.029E-03	2.028
5000	0.076	8.923E-05	1.177E-03	2.580
5500	0.041	5.388E-05	1.330E-03	3.206
6000	0.020	2.979E-05	1.487E-03	3.911
6500	0.009	1.508E-05	1.648E-03	4.694
7000	0.004	6.981E-06	1.812E-03	5.559
7500	0.001	2.956E-06	1.980E-03	6.507
8000	0.001	1.144E-06	2.150E-03	7.539
8500	0.000	4.040E-07	2.324E-03	8.657
9000	0.000	1.301E-07	2.501E-03	9.863
9500	0.000	3.820E-08	2.680E-03	11.158



Calculation of Fitting Parameters for 1 inch Flaw Sizes
2.000
1.000
0.000
-1.000
-2.000
-3.000
y = 2.2817x - 18.486
lnln(1/1-F(t))
7.000
7.250
7.500
7.750
8.000
8.250
8.500
ln(t)

Table B7

Time to develop 25, 5 inch flaw sizes over a length of 1 mile.

Observation Number	Time (years)	Time (days)	ln(t)	lnln(1/1-F(t))
1	7	2555	7.846	-2.013
2	8	2920	7.979	-1.246
3	10.4	3796	8.242	-0.755
4	13	4745	8.465	-0.367
5	14.7	5365.5	8.588	-0.019
6	16.7	6095.5	8.715	0.327
7	18.5	6752.5	8.818	0.732
8	20	7300	8.896	

Slope	Intercept
2.5268	-21.649

κ	λ
2.5268	0.00019

Fitting Parameters

Table B8

Various Lifetime Distributions for 5 inch Flaw Sizes

Time (Days)	S(t)	f(t)	h(t)	H(t)
500	0.997	1.319E-05	1.322E-05	0.003
1000	0.985	3.753E-05	3.810E-05	0.015
1500	0.959	6.785E-05	7.076E-05	0.042
2000	0.917	1.006E-04	1.098E-04	0.087
2500	0.858	1.325E-04	1.543E-04	0.153
3000	0.785	1.601E-04	2.039E-04	0.242
3500	0.700	1.805E-04	2.580E-04	0.357
4000	0.606	1.917E-04	3.163E-04	0.501
4500	0.509	1.929E-04	3.787E-04	0.674
5000	0.415	1.845E-04	4.448E-04	0.880
5500	0.326	1.679E-04	5.144E-04	1.120
6000	0.248	1.456E-04	5.875E-04	1.395
6500	0.181	1.203E-04	6.639E-04	1.708
7000	0.128	9.480E-05	7.434E-04	2.059
7500	0.086	7.116E-05	8.260E-04	2.452
8000	0.056	5.087E-05	9.115E-04	2.886
8500	0.035	3.461E-05	9.999E-04	3.364
9000	0.021	2.239E-05	1.091E-03	3.886
9500	0.012	1.377E-05	1.185E-03	4.455

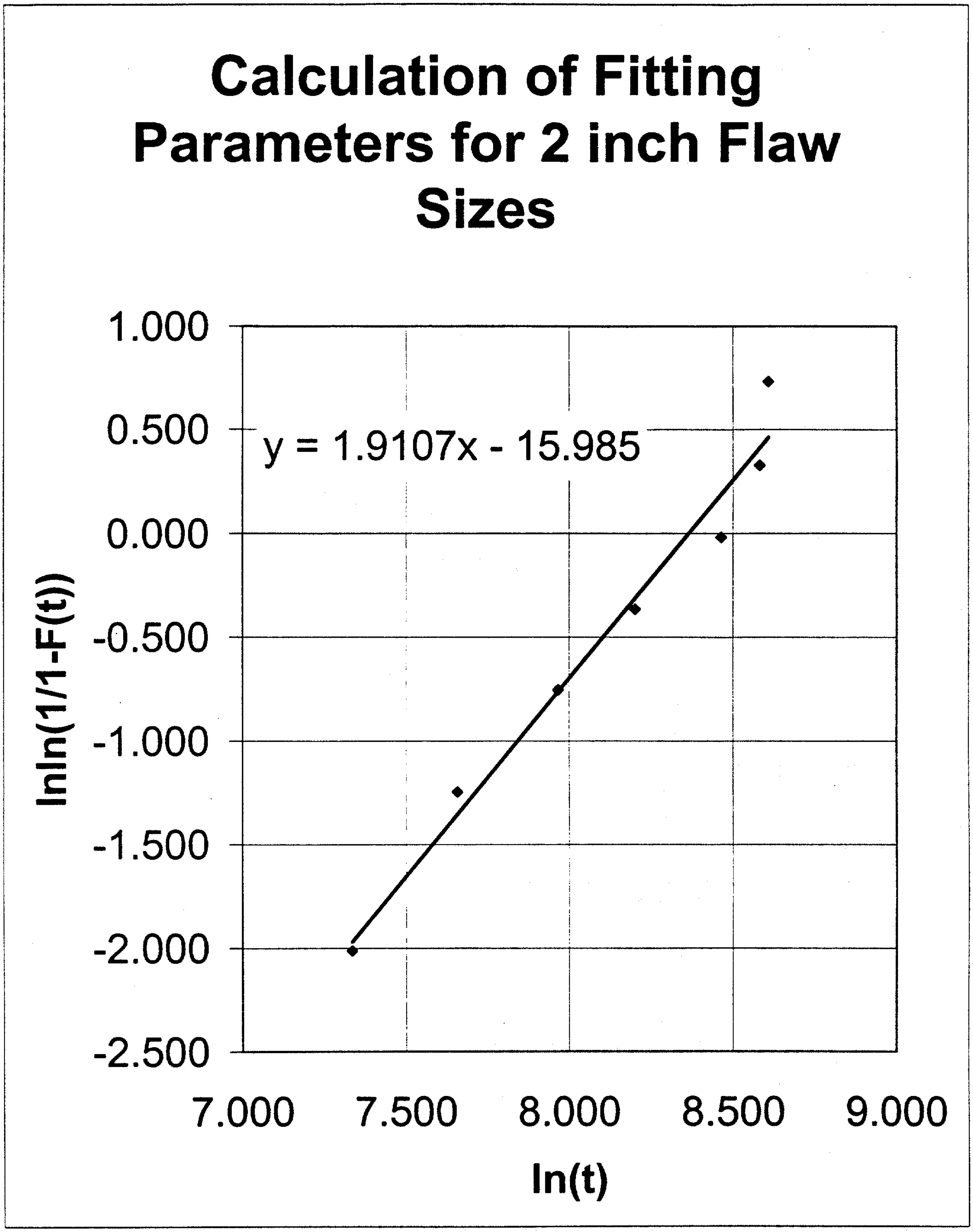

Calculation of Fitting Parameters for 2 inch Flaw Sizes
y = 1.9107x - 15.985
1.000
0.500
0.000
-0.500
-1.000
-1.500
-2.000
-2.500
lnln(1/1-F(t))
7.000
7.500
8.000
8.500
9.000
ln(t)

Table B5

Time to develop 75, 2 inch flaw sizes over a length of 1 mile.

Observation Number	Time (years)	Time (days)	ln(t)	lnln(1/1-F(t))
1	4.2	1533	7.335	-2.013
2	5.8	2117	7.658	-1.246
3	7.9	2883.5	7.967	-0.755
4	10	3650	8.202	-0.367
5	13	4745	8.465	-0.019
6	14.6	5329	8.581	0.327
7	15	5475	8.608	0.732
8	18	6570	8.790	

Slope	Intercept
1.9107	-15.985

κ	λ
1.9107	0.000233

Fitting Parameters

Table B6

Various Lifetime Distributions for 2 inch Flaw Sizes

Time (Days)	S(t)	f(t)	h(t)	H(t)
500	0.984	6.163E-05	6.265E-05	0.016
1000	0.940	1.107E-04	1.178E-04	0.062
1500	0.875	1.491E-04	1.704E-04	0.134
2000	0.793	1.756E-04	2.214E-04	0.232
2500	0.701	1.902E-04	2.713E-04	0.355
3000	0.605	1.937E-04	3.203E-04	0.503
3500	0.509	1.876E-04	3.686E-04	0.675
4000	0.418	1.741E-04	4.163E-04	0.871
4500	0.336	1.556E-04	4.634E-04	1.091
5000	0.263	1.343E-04	5.101E-04	1.335
5500	0.202	1.122E-04	5.563E-04	1.601
6000	0.151	9.088E-05	6.022E-04	1.891
6500	0.110	7.151E-05	6.478E-04	2.204
7000	0.079	5.472E-05	6.930E-04	2.539
7500	0.055	4.074E-05	7.379E-04	2.897
8000	0.038	2.955E-05	7.826E-04	3.277
8500	0.025	2.088E-05	8.270E-04	3.679
9000	0.017	1.439E-05	8.712E-04	4.104
9500	0.011	9.668E-06	9.152E-04	4.550

Calculation of Fitting Parameters for 5 inch Flaw Sizes

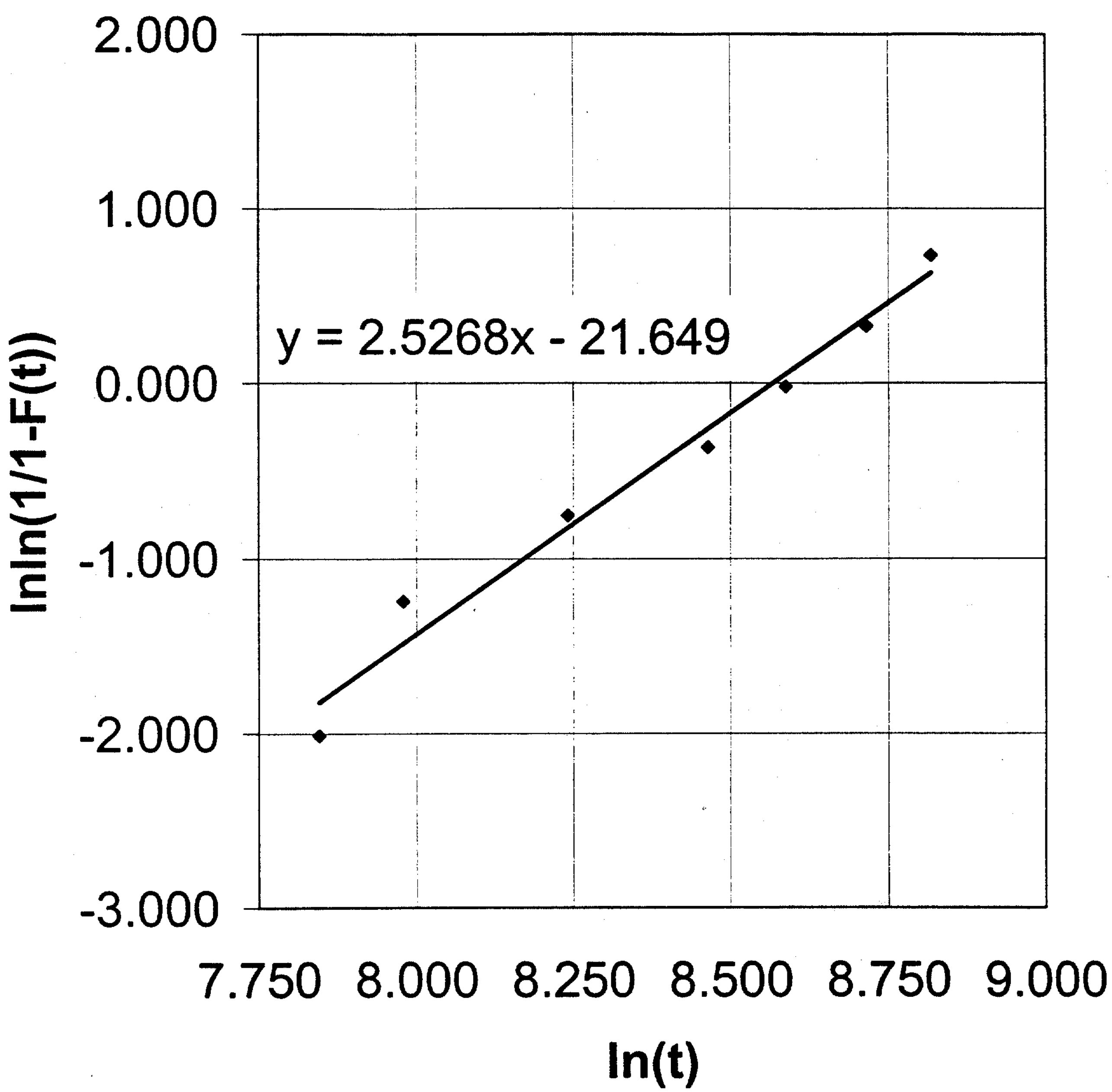


Table B9

Time to develop 5, 8 inch flaw sizes over a length of 1 mile.

Observation Number	Time (years)	Time (days)	ln(t)	lnln(1/1-F(t))
1	9.6	3504	8.162	-2.013
2	12	4380	8.385	-1.246
3	14.2	5183	8.553	-0.755
4	16	5840	8.672	-0.367
5	17.4	6351	8.756	-0.019
6	19.9	7263.5	8.891	0.327
7	21	7665	8.944	0.732
8	22	8030	8.991	

Slope	Intercept
3.3678	-29.519

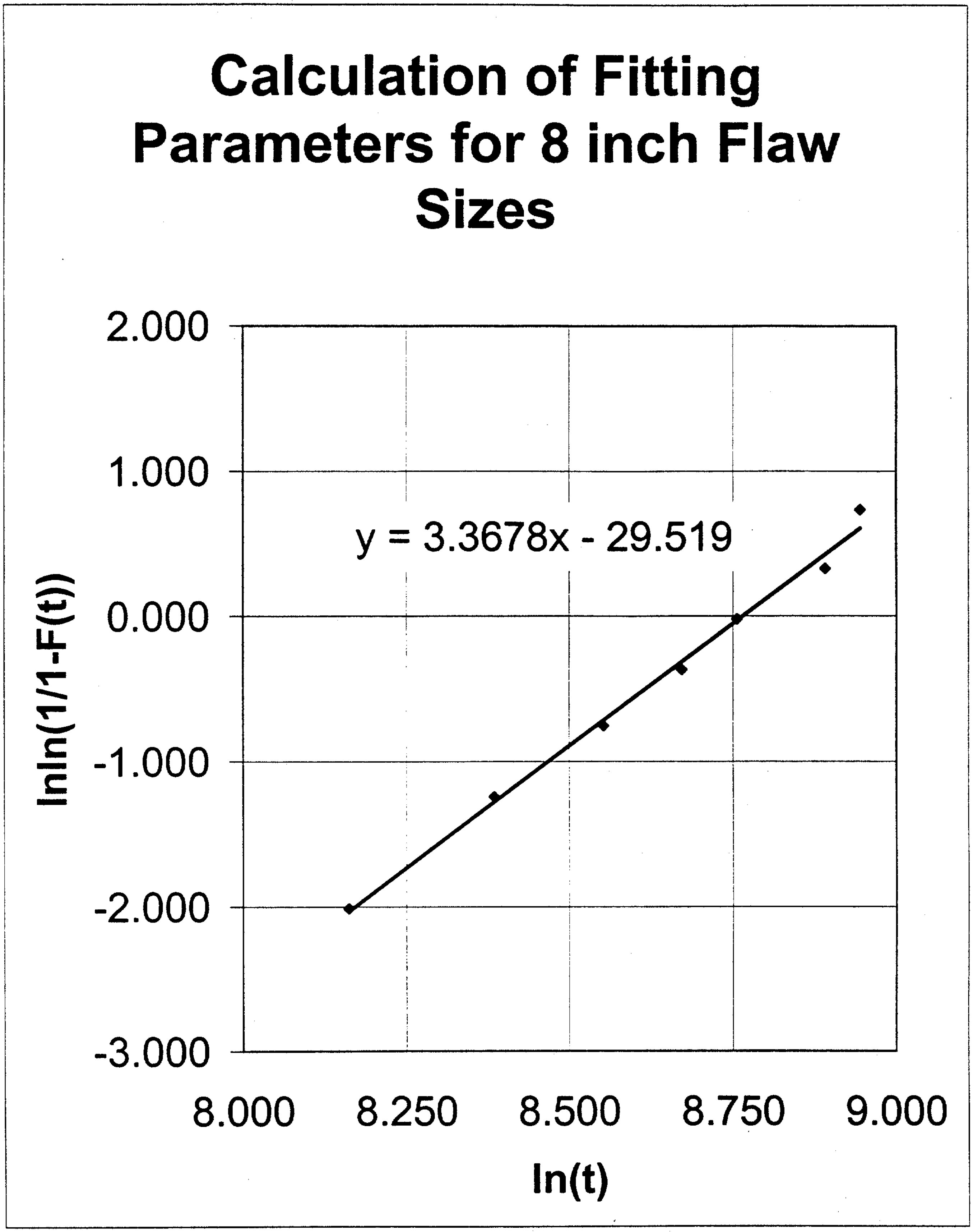
κ	λ
3.3678	0.000156

Fitting Parameters

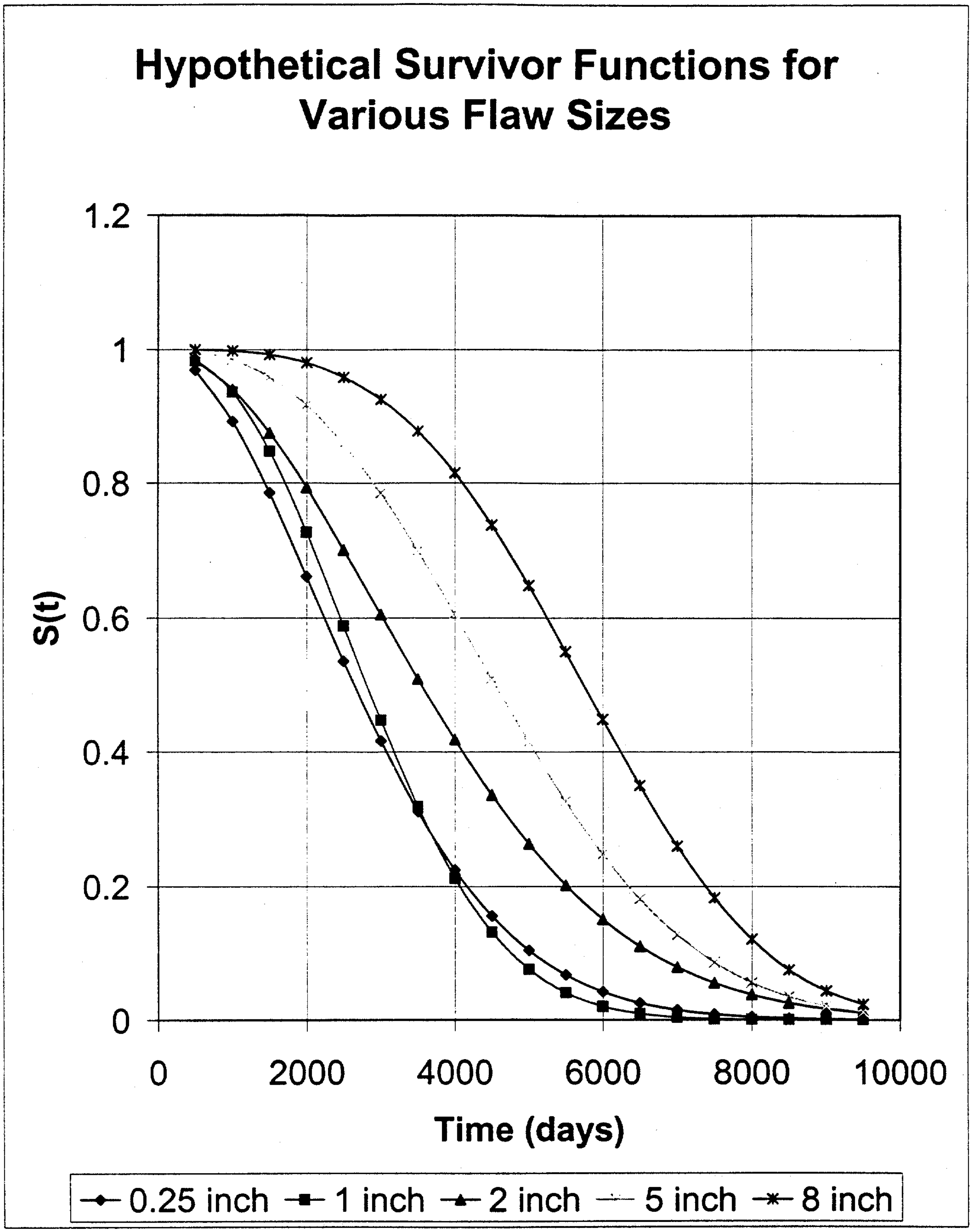
Table B10

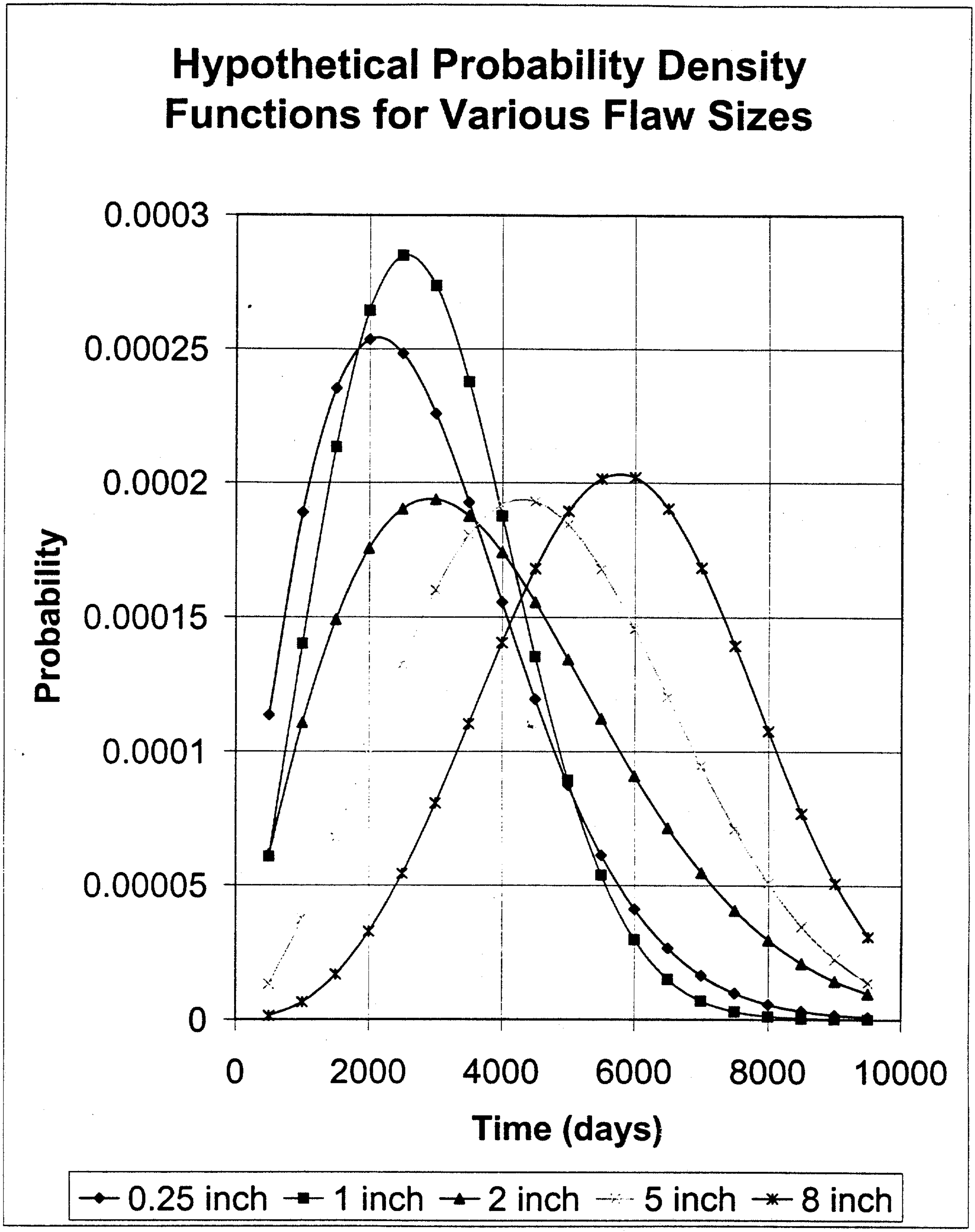
Various Lifetime Distributions for 8 inch Flaw Sizes

Time (Days)	S(t)	f(t)	h(t)	H(t)
500	1.000	1.253E-06	1.253E-06	0.000
1000	0.998	6.456E-06	6.469E-06	0.002
1500	0.993	1.677E-05	1.689E-05	0.008
2000	0.980	3.273E-05	3.339E-05	0.020
2500	0.959	5.430E-05	5.663E-05	0.042
3000	0.925	8.069E-05	8.720E-05	0.078
3500	0.878	1.102E-04	1.256E-04	0.131
4000	0.815	1.404E-04	1.723E-04	0.205
4500	0.738	1.680E-04	2.278E-04	0.304
5000	0.648	1.894E-04	2.923E-04	0.434
5500	0.550	2.014E-04	3.663E-04	0.598
6000	0.448	2.019E-04	4.501E-04	0.802
6500	0.350	1.904E-04	5.440E-04	1.050
7000	0.260	1.685E-04	6.484E-04	1.348
7500	0.183	1.394E-04	7.634E-04	1.700
8000	0.121	1.075E-04	8.895E-04	2.113
8500	0.075	7.691E-05	1.027E-03	2.592
9000	0.043	5.080E-05	1.176E-03	3.142
9500	0.023	3.083E-05	1.336E-03	3.769

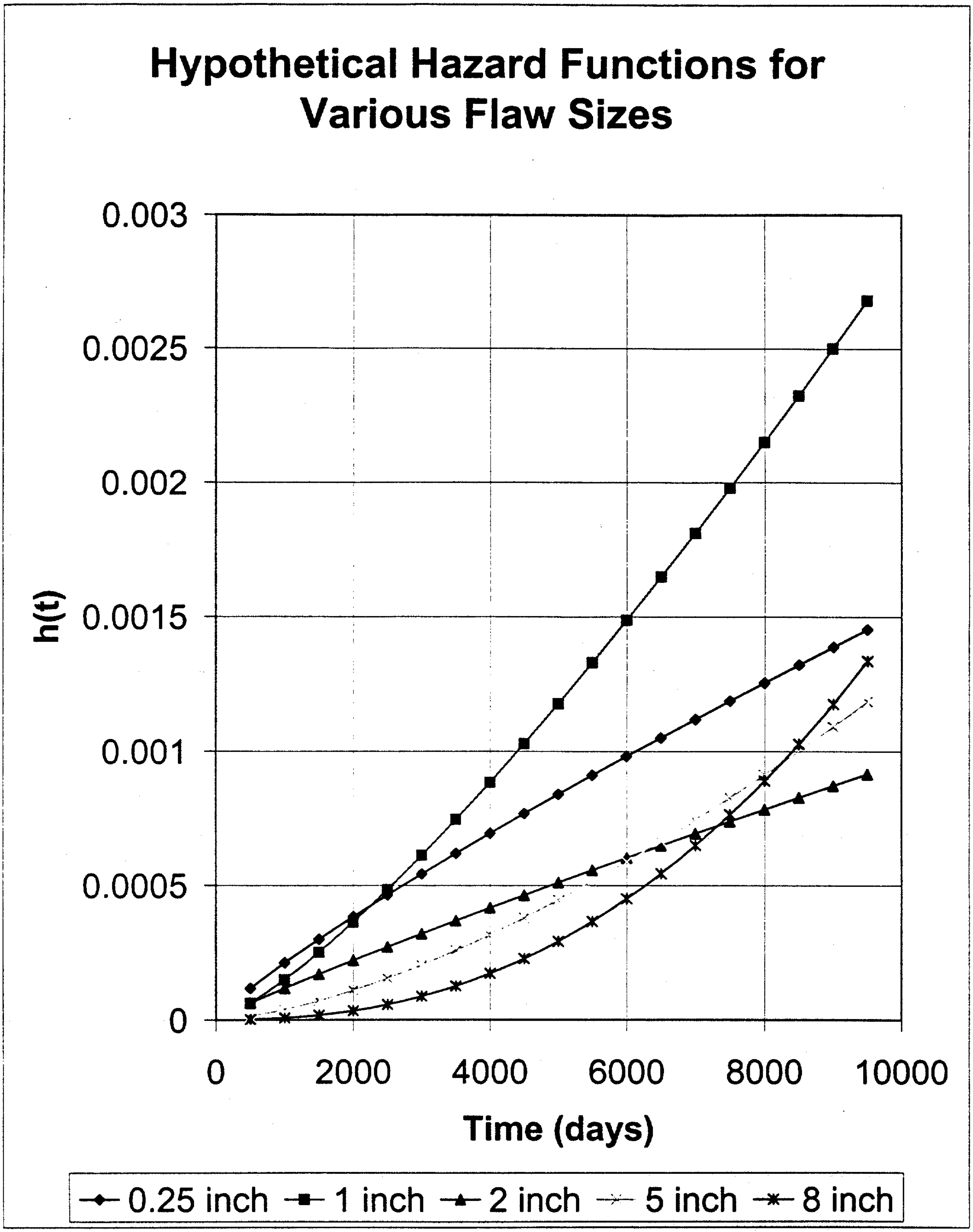


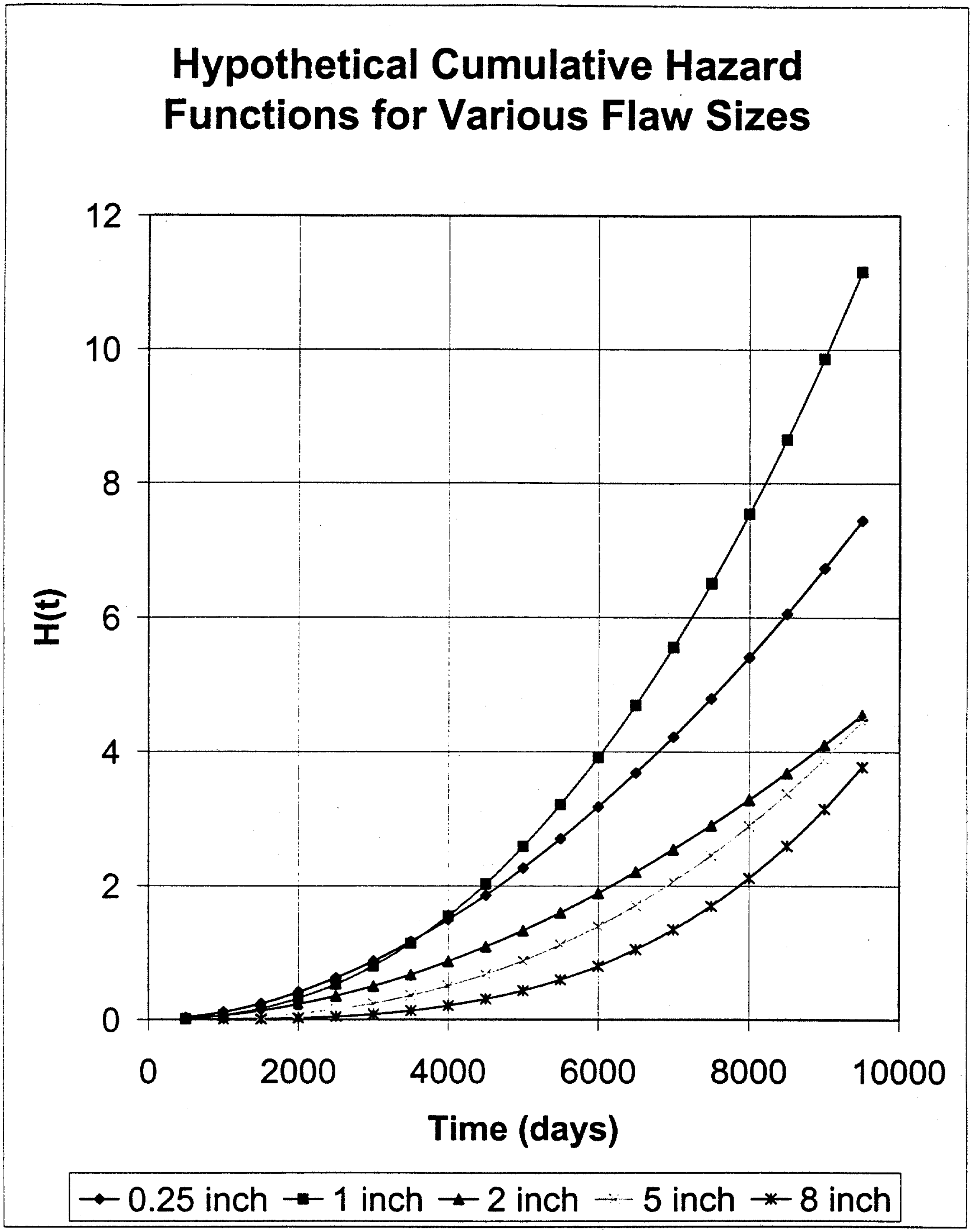
Calculation of Fitting Parameters for 8 inch Flaw Sizes
y = 3.3678x - 29.519
2.000
1.000
0.000
-1.000
-2.000
-3.000
8.000
8.250
8.500
8.750
9.000
lnln(1/1-F(t))
ln(t)


Hypothetical Survivor Functions for Various Flaw Sizes
S(t)
1.2
1
0.8
0.6
0.4
0.2
0
0
2000
4000
6000
8000
10000
Time (days)
0.25 inch
1 inch
2 inch
5 inch
8 inch



Hypothetical Probability Density Functions for Various Flaw Sizes
0.0003
0.00025
0.0002
0.00015
0.0001
0.00005
0
Probability
0
2000
4000
6000
8000
10000
Time (days)
0.25 inch
1 inch
2 inch
5 inch
8 inch


Hypothetical Hazard Functions for
Various Flaw Sizes
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
h(t)
0
2000
4000
6000
8000
10000
Time (days)
0.25 inch
1 inch
2 inch
5 inch
8 inch



Hypothetical Cumulative Hazard Functions for Various Flaw Sizes
H(t)
12
10
8
6
4
2
0
0
2000
4000
6000
8000
10000
Time (days)
0.25 inch
1 inch
2 inch
5 inch
8 inch